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INFLUENCE OF TEMPERING, PRESTRAINING, AND RETEMPERING ON THE STRENGTH AND TOUGHNESS OF HIGH-STRENGTH 4340 STEEL

TECHNICAL REPORT

by

EUGENE DiCESARE

AUGUST 1967

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ARMY MATERIALS AND MECHANICS RESEARCH CENTER
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INFLUENCE OF TEMPERING, PRESTRAINING, AND RETEMPERING ON THE STRENGTH AND TOUGHNESS OF HIGH-STRENGTH 4340 STEEL

ABSTRACT

The influence of tempering, prestraining, and retempering on the strength and toughness of martensitic and bainitic 4340 steel rods was investigated. The initial heat treatment consisted of a quench and temper to obtain martensite in one group and formation of bainite at 575 F followed by tempering in the second group. Reductions of area of 4 to percent were effected by cold drawing through a die with and without backpull, followed by a retempering treatment. Ultimate tensile strengths approaching 385,000 psi for the martensitic structure and 283,000 psi for the bainitic structure resulted with yield-tensile strength ratios approaching unity. Notch tensile strength of the bainite was superior to that of martensite at comparable strength levels. The prestraining also caused a yield point drop and/or serrations in the flow curves. This was influenced by specimen test temperature and strain rate, tempering temperature, and retempering temperature.

CONTENTS

INTRODUCTION

The problem of improving the strength level of alloy steels while maintaining an acceptable level of toughness has been of prime concern in recent years. Several general areas have been investigated including development of new alloys, heat treatment, processing techniques, and combinations of these. The new alloys have resulted in development of the maraging steels,[1] while the heat treatment and processing techniques have received attention through the development of thermomechanical treatments.[2] Thermomechanical treatments result in the greatest strength increases, and for some treatments, such as deformation of austenite prior to transformation to martensite, also result in improved toughness. Primary interest has been in martensitic microstructures although the bainitic structure is receiving increasingly more attention.

The mechanism by which steel is strengthened, in addition to the primary strain hardening on prestraining and retempering, has been the subject of several investigations. The most recent studies have resulted in the development of tentative theories. While differing somewhat in the mechanics of the strengthening process, there is general agreement in the theory that carbides and/or carbon play a major role, the strengthening being due to some type of interaction with the dislocations caused by heat treatment and/or straining. It has been suggested that vacancies created by deformation are a more likely site for the interaction with the carbon atoms.[3]

Stephenson and Cohen[4] attained a maximum tensile strength of approximately 340,000 psi in 4340 tempered martensite (400 F) by prestraining tension test specimens approximately 3 percent, and retempering at 400 F. Stable elongation was zero. They also noted a yield point phenomenon in the form of necking and a yield point drop immediately following maximum load.

This yield point phenomenon was also noted by Breyer and Polakowski[5] in 4340 martensite prestrained by drawing through a die. It was shown to be present for reduction of 3.09 to 8.92 percent, tempers up to 500 F, and retempers up to 300 F. The maximum tensile and yield strengths obtained were 396,000 and 387,000 psi, respectively.

Several investigations have been conducted in which the mechanical properties of the martensitic and bainitic microstructures have been compared. Kalish, Kulin, and Cohen[6] investigated the effect of applying a prestrain and retemper treatment to martensitic and bainitic 4350 steel. Deformations of up to 50 percent by rolling were conducted on the specimens before and after transformation, followed by a retempering treatment. It was found that the strengthening obtained by straining both prior to and after transformation to martensite was additive, resulting in a maximum yield strength of approximately 330,000 psi. For the bainite, the amount of strengthening due to straining prior to transformation was negligible, the only strengthening being that due to deformation after transformation. A maximum yield strength of approximately 300,000 psi resulted. A refrigeration treatment following the quench, prior to tempering, was found to improve the properties by reducing the amount of retained austenite.

Harthower and Orner[7] found that for a 200,000-psi yield strength, the toughness of bainite is comparable to that of martensite when tested at room temperature but that martensite is tougher at lower temperatures.

Banerjee and Hauser[8] observed that 4340 tempered martensite is tougher than tempered lower bainite at comparable strength levels.

A study of 4350, 4360, and 4320 low-alloy steels by Simcoe and Shehan[9] led to the conclusion that the minimum carbon content required to form high-strength bainite was 0.55 percent. Fracture toughness of bainite formed 25 F or more above the M_s is equal to or slightly better than that of martensite, while bainite formed at lower temperatures was found to have slightly lower toughness than martensite, at comparable strength levels.

Although the prestrain and retemper thermomechanical treatment for obtaining ultrahigh-strength levels has been applied by several researchers, the process has received minimal attention in several areas:

1. The effect of the tempering temperature, in the low temperature range of room temperature to approximately 600 F, on the notch tensile strength and true stress-true strain properties of prestrained and retempered martensite.

2. Evaluation, for the bainite microstructure, of the comparative engineering and true stress-true strain mechanical properties and notch tensile properties, resulting from the prestrain and retemper cycle.

3. The effect of straining by drawing through a die. The stress system differs from that imposed by the widely used rolling process and would be expected to affect some mechanical properties.

The objective of this work was to obtain experimental data in these areas to further understand the prestrain and retemper process. Steel rods of the 4340 alloy were drawn (with and without a back-pull) through a die to impart a 4 to 5 percent reduction of area after formation of either tempered martensite (room temperature to 600 F) or bainite formed at 575 F and tempered at room temperature, 400 F, and 700 F. This prestraining was followed by a retempering treatment (room temperature to 700 F for the martensite and room temperature to 750 F for the bainite). The smooth, true stress-true strain, and notch tensile properties of the martensitic and bainitic rods have been correlated with the tempering, prestraining, and retempering temperatures. A limited examination was also conducted to determine the effect of test temperature and strain rate on the yield point phenomenon which was observed in this and previously referenced papers.

The importance of the tempering and retempering treatments and the contrast in behavior of the martensitic and bainitic structures were emphasized by the broad range of properties resulting in the former as compared to the minimal changes in the mechanical properties of the latter. This would be expected in view of the higher temperature of bainite formation (575 F). The

true stress-true strain tests, however, emphasize the basic similarities between the behavior of the martensitic and bainitic microstructures as the conditions for which a yield point phenomenon and serrated flow are developed and are comparable. This may indicate similar strengthening mechanisms, in the prestrain and retemper process, for both the martensitic and bainitic microstructures.

While the properties of the martensite which may be compared follow the same general trends as those reported by others, the magnitudes differ. The results also show the notch strength of the bainite to be superior to martensite at comparable strength levels as contrasted to the marginal toughness differences reported by others. The application of a back-pull during the prestrain was expected to affect the properties by reducing the redundant work and friction, thus more nearly approaching the stress conditions present in a tension test prior to the onset of necking. Although the results are inconclusive, generally higher strength levels were observed for rods prestrained using a back-pull. The data are presented; however, the effect of back-pull is not discussed in view of the minimal trends which were noted.

The report is presented under three headings: Engineering Tensile Properties, True Stress-True Strain Properties, and Notch Tensile Properties. Each section is devoted to a comparison of the effect of tempering, prestraining, and retempering on these properties for both the martensitic and the bainitic microstructures.

MATERIAL AND PROCEDURE

Cold-drawn annealed 4340 steel rod, 1/2-inch o.d. was used. This was from a single heat of aircraft-quality steel with the following chemical analysis: 0.395 C, 0.71 Mn, 0.31 Si, 1.76 Ni, 0.79 Cr, 0.22 Mo, 0.012 P, 0.008 S, and 0.012 N.

The rods were swaged to the diameter required to permit the desired reductions when drawn through a die with a 0.4096-inch-diameter opening. Heat treatment was as follows to obtain either a martensitic or a bainitic microstructure:

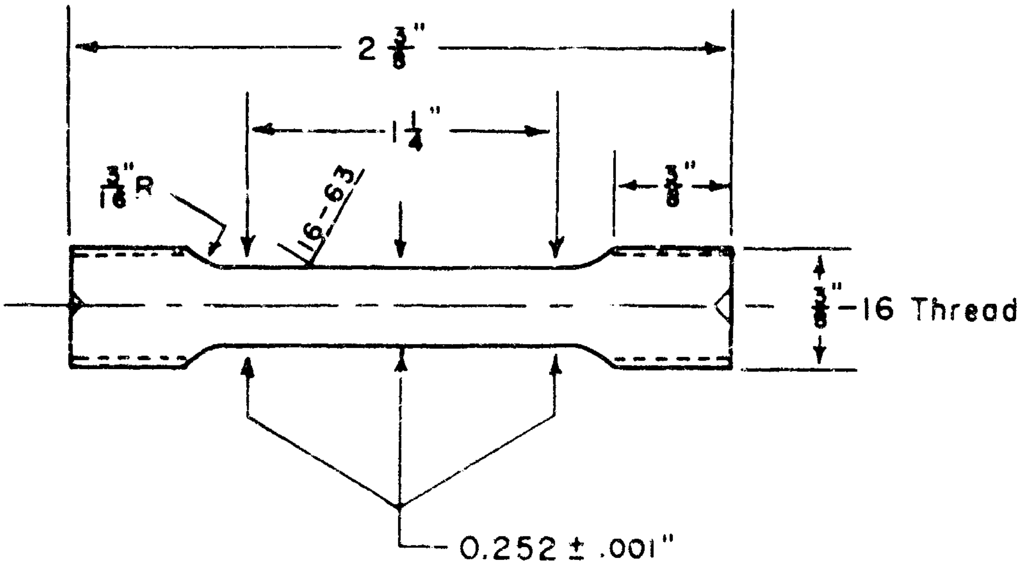
Martensite - Normalize 1650 F, 1 hour, air cool
Austenitize 1550 F, 1 hour, oil quench
Liquid nitrogen, 10 minutes
Temper (RT, 200, 300, 400, 500, 600 F), 1 hour

Bainite - Normalize 1650 F, 1 hour, air cool
Austenitize 1550 F, 1 hour
Quench into salt at 575 F, hold 1 hour
Quench into brine at room temperature
Liquid nitrogen, 10 minutes
Temper (RT, 200, 400, 700 F), 1 hour

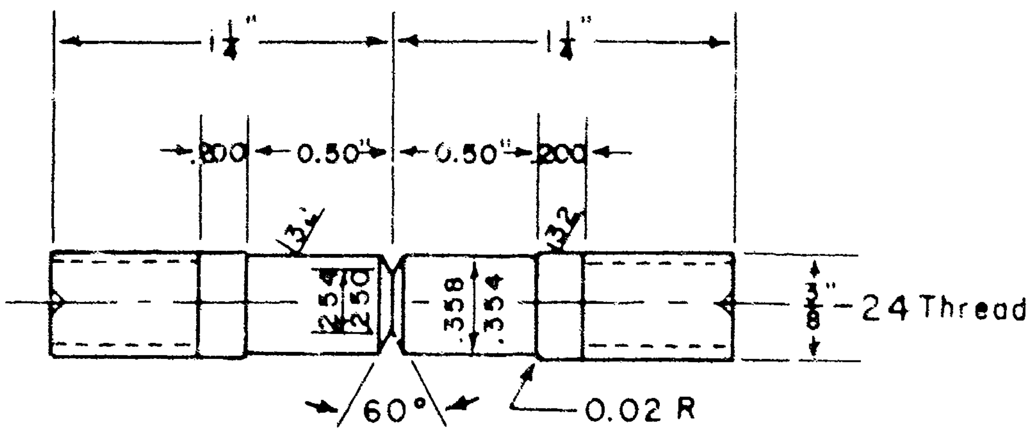
They were then cleaned by shot blasting, and lubricated with drawing oil.

The rods tempered at 300 F and above were phosphatized prior to lubricating. The rods were then drawn through a die on the rod and wire drawing machine.[10] The die contour was changed to introduce a 1 percent reduction in the bearing area following the primary reduction. This was done to impart a compressive stress to the surface and minimize the problem of cracking due to the tensile stresses resulting from the standard die contour.

The drawn rods were cut into appropriate lengths for smooth and notch tensile blanks and retempered at the various temperatures. The tensile blanks were then machined to the dimensions shown in Figure 1. The notch radii of the notched tension specimens were machined to 0.0008 inch or less,



a. Threaded True Stress-True Strain Tensile Specimen



Notch Radius to be 0.0003 to 0.0007

b. Notch Tensile Specimen

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Figure 1 TEST SPECIMENS

mostly 0.0005 to 0.0008 inch. A special ASTM Committee[11] indicates that the notch test is not sensitive to toughness variations when the notch strength ratio equals or exceeds approximately $2 - d^2/D^2$ for low-alloy heat-treated steels where D is the major diameter and d is the diameter at the notch root. This ratio (1.5 for these specimens) was not equalled or exceeded in any of the tests.

The smooth bars were tested at a strain rate of 0.01 min^{-1} using an extensometer to obtain the 0.2 percent yield strength. The extensometer was then removed, while loading continued, and the true stress-true strain device[12] started to monitor continuously the minimum diameter of the tension bar and the corresponding load. These values were recorded on an oscillograph recorder and used to calculate the true stress and true strain. A special alignment fixture was used in testing the notched specimens. The complete processing and mechanical property data are presented in Tables I and II in the Appendix.

ENGINEERING TENSILE PROPERTIES

Effect of Heat Treatment

Martensite

The variation in tensile and yield strengths and reduction of area with tempering temperature is shown in Figure 2. The tensile strength decreases continuously with increasing tempering temperature; however, the yield strength goes through a maximum at about 400 F. As a result, the spread of 130,000 psi between yield and tensile strengths for an untempered structure, room temperature, decreases to a minimal 10,000 psi spread for tempers above 800 F. The reduction of area is not affected on tempering between 400 F and 1000 F. There is a decrease in reduction of area on tempering below 400 F and an increase on tempering at 1150 F.

These trends are normal for the heat-treated (quench and temper) condition.

Bainite

Behavior of the bainitic material on tempering is quite different as shown also in Figure 2. Due to the high temperature of bainite formation, 575 F, a tempering effect is found only for the 700 F temper, i.e., a slight drop in tensile strength and a slight increase in yield strength. The reduction of area is not affected.

Effect of Prestraining and Retempering

Martensite

Figure 3 shows the tensile properties and Figure 4 the change in tensile properties resulting from the prestrain and retemper processing. The data

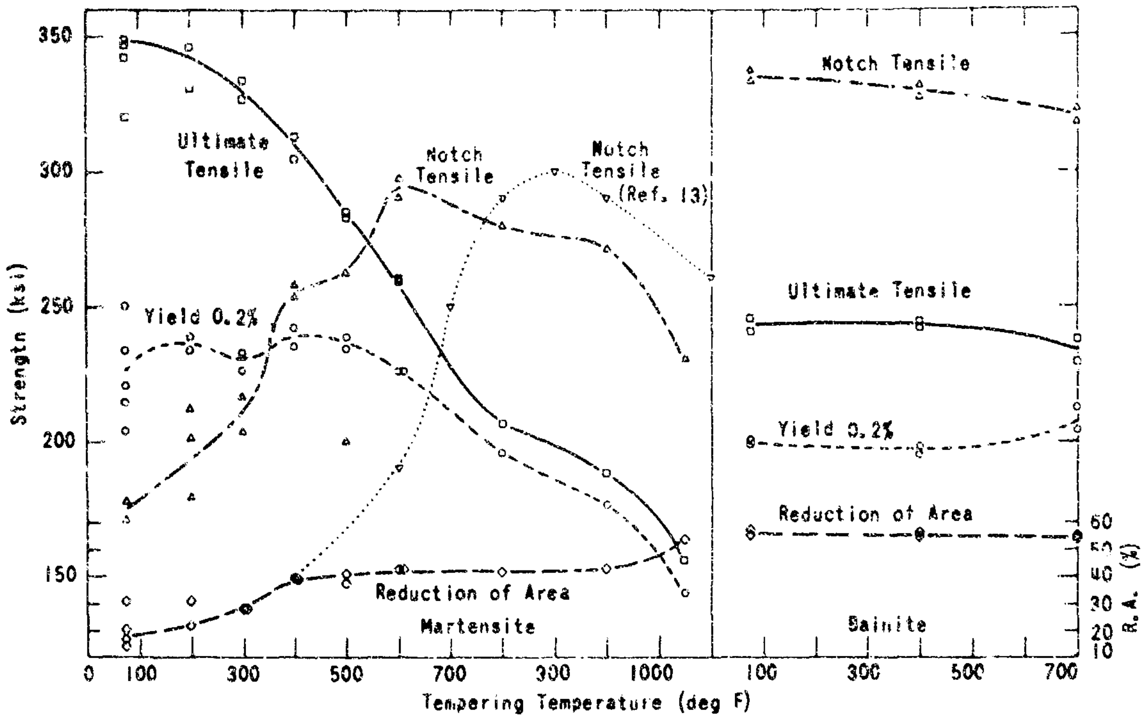

Figure 2. TEMPERED TENSILE PROPERTIES

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for the 800, 1000, and 1150 F tempering temperatures are taken from previous work[10] in which a 10 percent reduction was made, as compared to the present 4 to 5 percent reduction. The magnitude of these data is slightly higher than would be expected for a 4 to 5 percent reduction. In Figure 4, the base or zero point refers to the as-heat-treated condition.

The tensile strength of the martensite is raised by prestraining, the maximum increase (approximately 30,000 psi) occurring for the rods initially tempered between room temperature and 400 F. The yield strength is also increased on prestraining, the maximum increase being approximately 150,000 psi for rods initially tempered at room temperature. This decreases to approximately 10,000 psi for the rods initially tempered at 800 F and higher.

Retempering the prestrained rods at 200 F has a negligible effect on the tensile and yield strengths. The effect of retempering at 400 F is dependent upon the initial tempering temperature. For initial tempering temperatures below 500 F, there is an essentially constant decrease in both the yield and tensile strengths compared to the as-prestrained values. For higher tempering temperatures, a constant increase instead of a decrease is found on retempering at 400 F.

Similarly, the effect of retempering at 700 F is dependent upon the tempering temperature, resulting in a decrease in the tensile and yield strengths, compared to the prestrained values, over the range of tempering

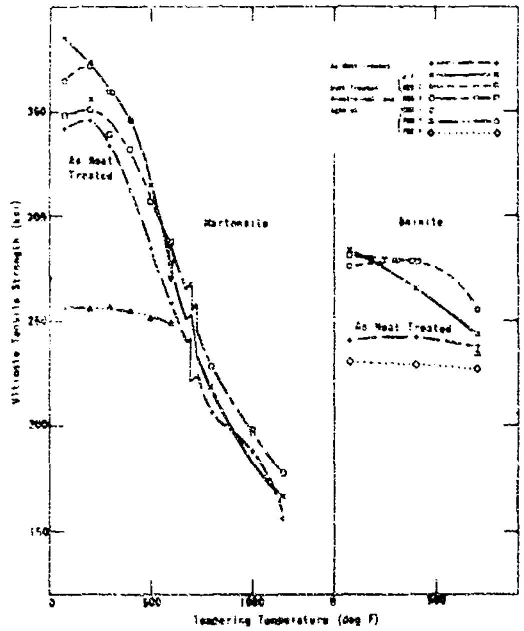
temperatures evaluated (up to 600 F). For tempering temperatures above 700 F an increase would be expected on retempering at 700 F. This is indicated by the projected intersection of the 700 F retempering temperature curve with the as-prestrained curve at approximately 700 F tempering temperature in Figures 3 and 4.

Generally, by retempering at a temperature which is equal to or higher than the initial tempering temperature, the tensile and yield strengths of the prestrained rods are decreased. On retempering at lower temperatures than the initial tempering temperatures, these values are increased.

Figure 5 shows the ultimate tensile strengths of the prestrained rods as a function of the tempering and retempering temperatures. These are compared to the data obtained by Stephenson and Cohen[4] and Breyer and Polakowski.[5] The tensile strengths agree with the results of Breyer and Polakowski, but are higher than those of Stephenson and Cohen. The refrigeration treatment used in this investigation to minimize the amount of retained austenite may account for the difference. Retained austenite was found to be less than 1 percent by X-ray analysis in both the martensitic and bainitic materials. This may also be due to the difference in stresses resulting from straining a tensile bar compared to those obtained by drawing through a die.

Bainite

The tensile properties and the changes in tensile properties resulting from the prestrain and retemper of the bainitic rods are also presented in Figures 3 and 4. An increase in the tensile and yield strengths is noted on prestraining, the magnitude increasing with decreasing initial tempering temperature.



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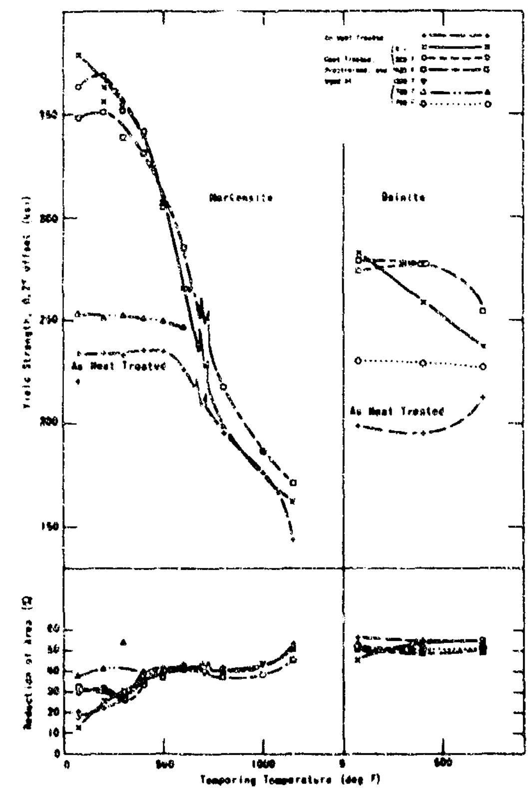

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Figure 3. TENSILE PROPERTIES OF PRESTRAINED AND RETEMPERED RODS

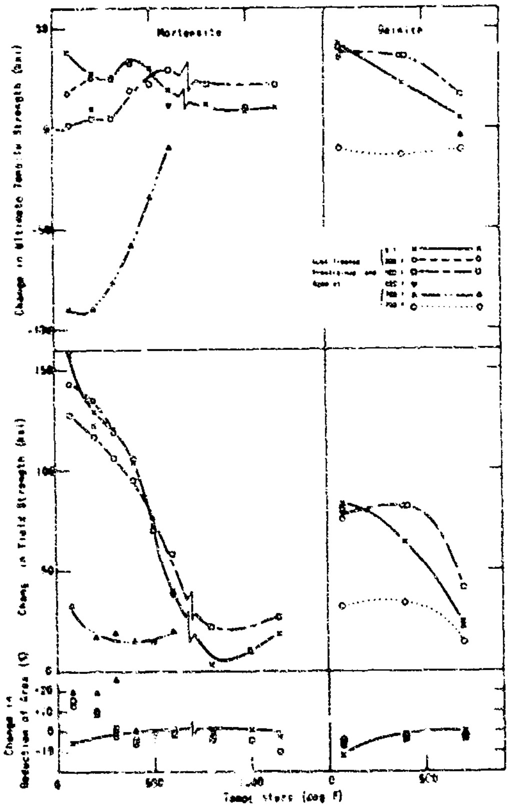

Figure 4. CHANGE IN TENSILE PROPERTIES OF RODS PRESTRAINED AND RETEMPERED

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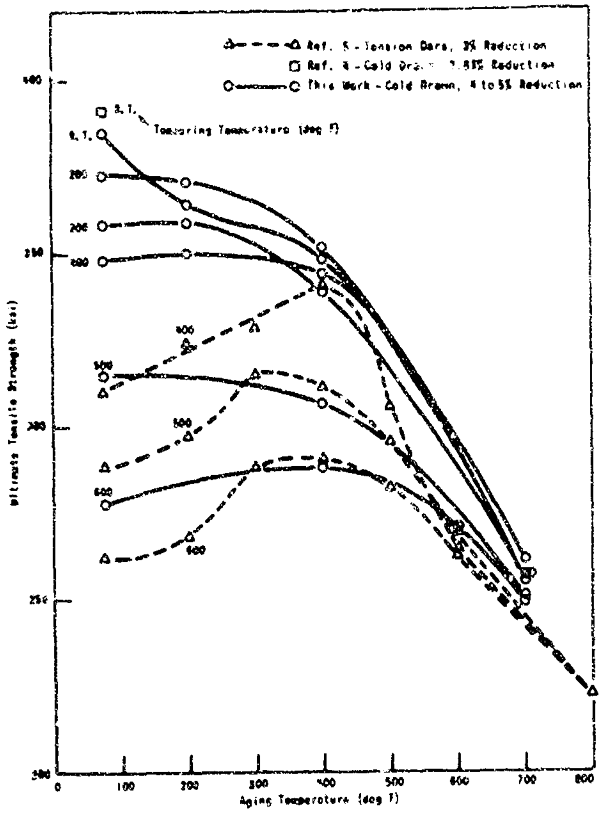

Figure 5. EFFECT OF PRESTRAINING AND RETEMPERING ON THE TENSILE STRENGTH OF MARTENSITE

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Retempering at 200 and 400 F increased by a constant amount the tensile and yield strengths of the prestrained rods which were initially tempered at 400 and 700 F. Those tempered at room temperature were not affected by the retemper. The 750 F retemper resulted in an appreciable decrease in the tensile and yield strengths compared to the prestrained values. This decrease on retempering at 750 F also resulted in lower tensile strengths and higher yield strengths compared to the values for the as-tempered condition.

The decrease in reduction of area does not exceed 10 percent on prestraining and retempering. In view of the high initial reduction of area, this is a minimal loss.

TRUE STRESS-TRUE STRAIN PROPERTIES

Effect of Heat Treatment

Martensite

True stress-true strain curves r tensile specimens tempered at room temperature, prestrained, and retempered are presented in Figure 6 as typical

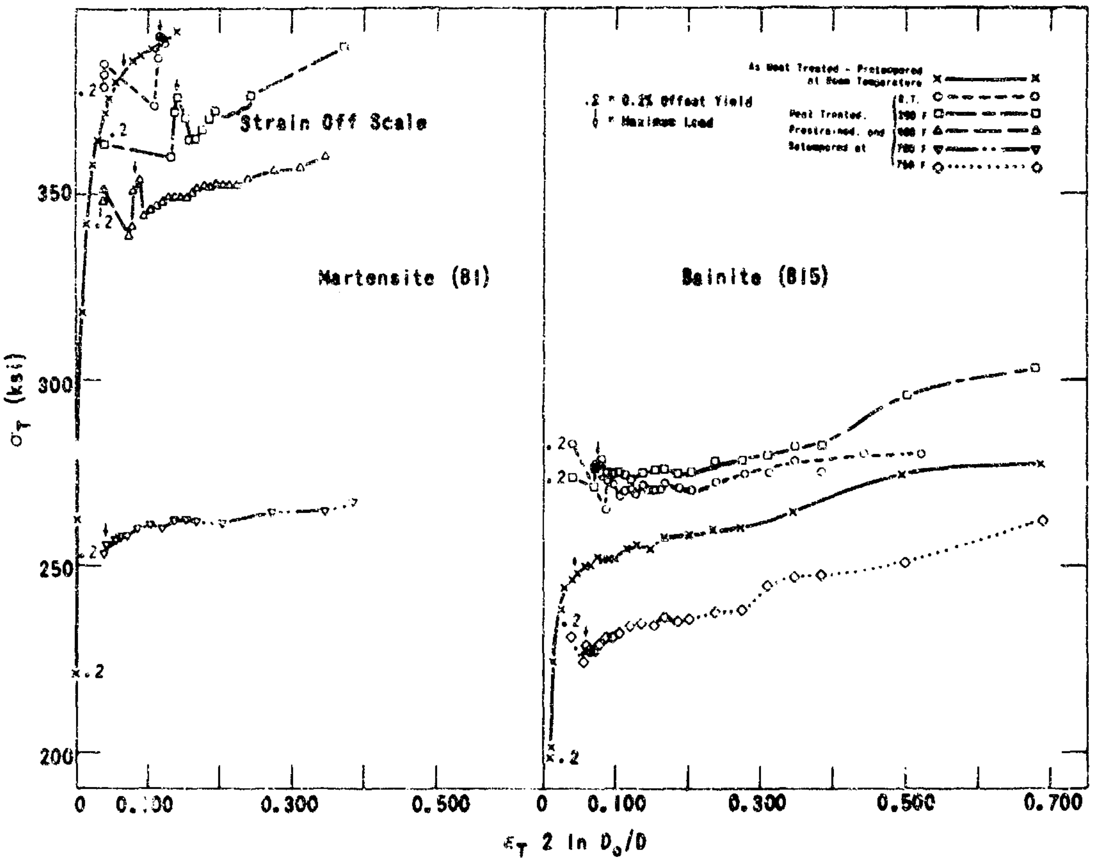

Figure 6. TRUE STRESS-TRUE STRAIN PROPERTIES OF MARTENSITE AND BAINITE TEMPERED AT ROOM TEMPERATURE, PRESTRAINED, AND RETEMPERED

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flow curves obtained for the martensitic and bainitic microstructures. The 0.2 percent yield strength, obtained with an extensometer, and the maximum load are also shown for each curve.

The curve for tempered martensite is smooth with no indication of a yield point drop; however, several curves for martensite tempered at higher temperatures (not shown) appear to have one or more short flat areas similar to those shown for the tempered bainite. These indicate a change in the rate of necking in the tensile specimen.

Bainite

The true stress-true strain curve for tempered bainite in Figure 6 shows that the necking beyond maximum load does not proceed at a uniform rate. This was also noted in other curves for tempered bainite. The true strain to fracture is generally greater than for the martensitic specimens.

The test temperature was found to have an interesting effect on the flow curves for tempered bainite as shown in Figure 7. A smooth curve resulted at

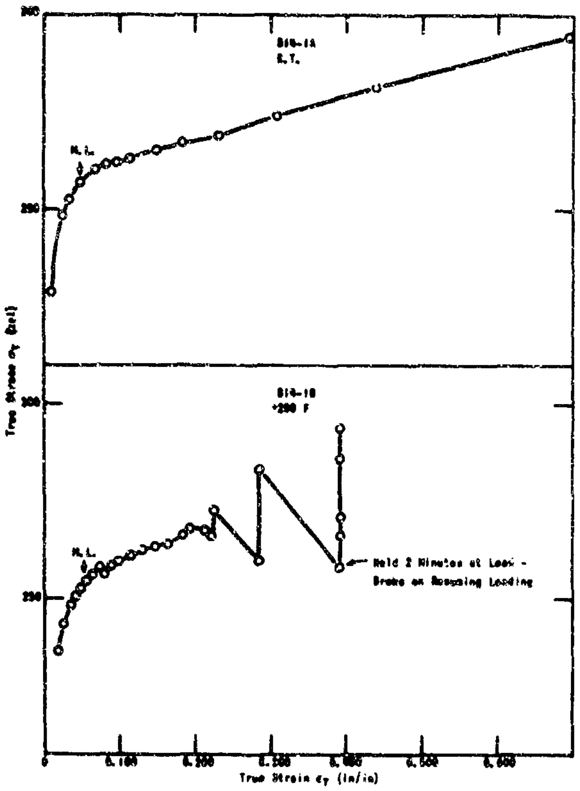

Figure 7. EFFECT OF TESTING TEMPERATURE ON THE FLOW CURVE OF TEMPERED BAINITE

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room temperature; however, testing at 200 F resulted in a small serration at a true strain of 0.073 followed by a second smoother serration at a true strain of 0.193, which was immediately followed by three sharp serrations increasing in magnitude to failure.

Effect of Prestraining and Retempering

Martensite

The most apparent effect of prestraining and retempering is the introduction of discontinuous yielding beyond the 0.2 percent yield, Figure 6. The first serration is the result of an instantaneous load drop and neck formation. The second and subsequent serrations are caused by further necking at the same location, but these do not occur as rapidly as the first nor are they of the same magnitude. The rate and magnitude of the effect is dependent upon the tempering and retempering temperatures, decreasing with increasing temperature.

The shape of the true stress-true strain curve is also dependent upon strain rate. Strain rates of 0.1, 0.01 (standard), and 0.005 min^{-1} were examined, as well as interrupted loading. The curves are shown in Figure 8 where for each strain rate only the initial load drop and neck formation are instantaneous. Further strain in the neck of the specimen and changes in the load continue at a slower rate. By releasing the load to zero after each drop, a series of serrations was produced, Figure 8d. A similar series of serrations could be initiated by holding the load constant for a limited time after each load drop, followed by an increase in the load, Figures 8c and 9e. The strain rate results indicate that a series of serrations may be expected to occur on continuous loading at a strain rate below 0.005 min^{-1}. Creep tests would be required to determine this strain rate.

Bainite

The true stress-true strain curves for these specimens are characterized by an initial yield point drop (Figure 6). The magnitude of the effect decreases with increasing retempering temperature.

The effects of interrupted loading and of test temperature on the flow curves were observed in the bainitic material. The test temperature effects

seen in Figure 9 indicate that temperature is an important factor in the development of serrations. At room temperature and -105 F (Figures 9a and b) only a yield point drop, or one serration, is noted; however, at 200 F (Figure 9d) serrations are initiated at the maximum load and are continuous, increasing in magnitude with strain. Interrupted loading at 200 F (Figure 9c) increased the magnitude of the serrations compared to those obtained on continuous loading at 200 F.

The slopes of the flow curves vary with test temperatures, the lowest being for -105 F and the highest for room temperature testing. Also, the magnitude of the yield stress may be raised by decreasing the test temperature or by interrupted loading. This may be observed by comparing the maximum load on testing at -105 F. The effect of interrupted loading, prior to the initial yield point drop, is apparent when the curves of Figures 9a and 9e are compared. The latter curve, obtained by discontinuous loading, exhibits an 11,000 psi increase in maximum load. Further discontinuous loading resulted in a serrated stress-strain curve similar to that obtained on testing the martensitic microstructure under comparable conditions.

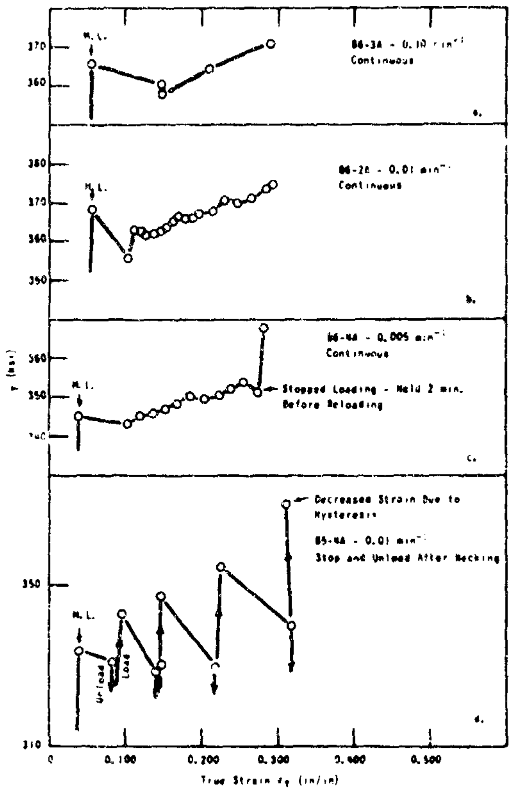

Figure 8. EFFECT OF STRAIN RATE ON THE FLOW CURVES OF PRESTRAINED RETEMPERED MARTENSITE AT ROOM TEMPERATURE

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An important difference between the serrations obtained with the tempered bainite and those obtained with the prestrained and retempered bainite at a test temperature of 200 F is the strain at which the serrations were initiated. In the former the serrations started at a true strain of approximately 0.200, well beyond the strain of 0.0523 at which maximum load was observed. In the latter, the serrations were initiated at maximum load and continued to failure.

NOTCH TENSILE PROPERTIES

Effect of Heat Treatment

Martensite

The notch tensile strength of the tempered martensite is shown in Figures 2 and 10 to be dependent upon the tempering temperature. From a low

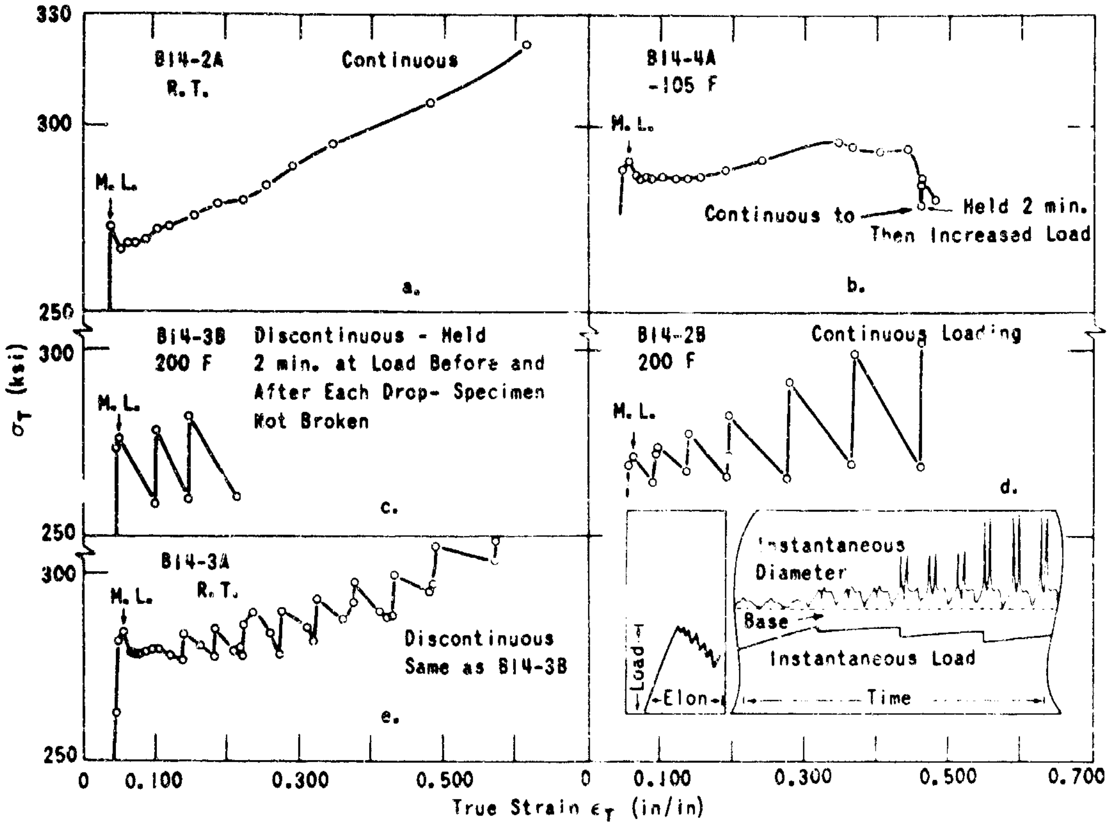

Figure 9. EFFECT OF TESTING TEMPERATURE AND INTERRUPTED LOADING ON THE FLOW CURVE OF PRESTRAINED AND RETEMPERED BAINITE

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notch tensile strength for the martensite tempered at room temperature, there is a linear increase to a maximum at 600 F, followed by a decrease at higher tempering temperatures. The N.T.S./Y.S. ratio equals 1 at approximately 350 F. The role of sharper notches (fatigue crack) would be to effect a more severe test, resulting in a sharper transition, and raising the temperature at which the ratio of N.T.S. to Y.S. equals 1. This is shown by the curve of notch tensile strength in Figure 2 as taken from Reference 13.

With reference to strength levels, Figure 2 and the data of Table I show that the notch tensile strength increases with increasing yield strength (lower tempering temperatures) to a maximum at a yield strength of approximately 225,000 psi. Tempering at lower tempering temperatures results in a minimal increase in yield strength but a rapid drop in the magnitude of the notch tensile strength.

Bainite

In contrast to the martensite, Figure 2 shows that the notch strength of the bainite decreases only a small amount with increasing tempering temperature. The N.T.S./Y.S. ratio is greater than 1 for all tempering temperatures.

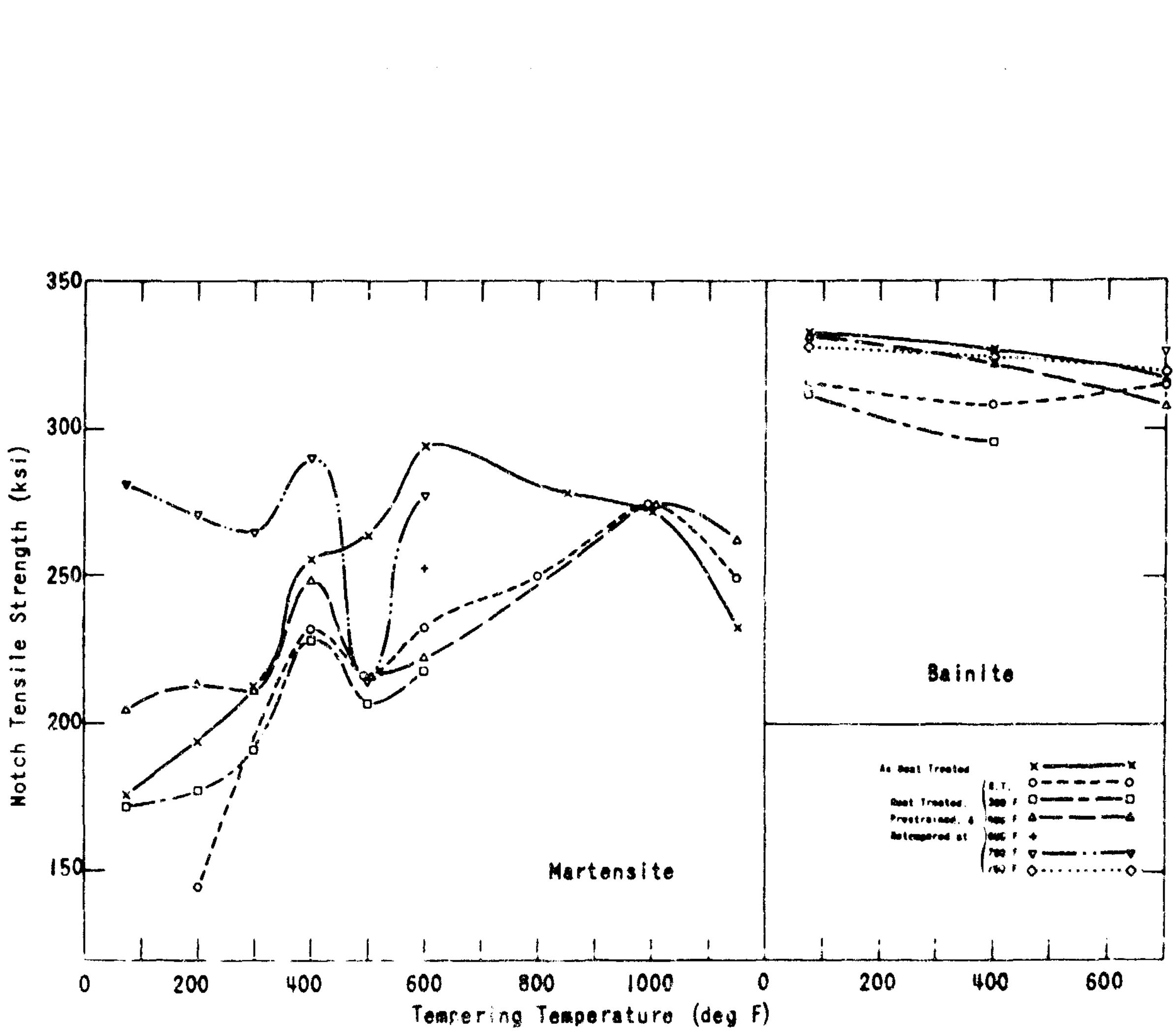

Figure 10. EFFECT OF PRESTRAINING AND RETEMPERING ON THE NOTCH TENSILE STRENGTH OF MARTENSITE AND BAINITE

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The variation in either notch tensile or yield strength is small for the range of tempering temperatures employed due to the high bainite formation temperature of 575 F.

Effect of Prestraining and Retempering

Martensite

Prestraining the rods resulted in generally lower notch strengths (Figure 10) compared to the values for the tempered condition. Only the rods tempered at 1000 and 1150 F show any improvement in notch strength

The effect of retempering on the notch strength is primarily dependent upon the tempering temperature. Retempering at 400 to 700 F is most beneficial to the rods initially tempered at the low temperatures. The notch strength was appreciably improved as compared to the tempered and the prestrained condition, particularly for the 700 F retempering treatment. The range of notch tensile strength is comparable to that observed for the tempered martensite; however, the yield strength is appreciably higher for the

prestrained and retempered specimens, 250,000 psi versus 210,000 psi for the tempered martensite.

Another interesting feature of the curves in Figure 10 is the peak in notch strength for the prestrained and retempered martensite which was initially tempered at 400 F. This is followed by lower notch tensile strengths for the martensite which was initially tempered at 500 F, and may be indicative of the 500 F embrittlement.

The relationship between notch tensile strength and yield strength is shown in Figure 11. The exact magnitudes are a function of the tempering and

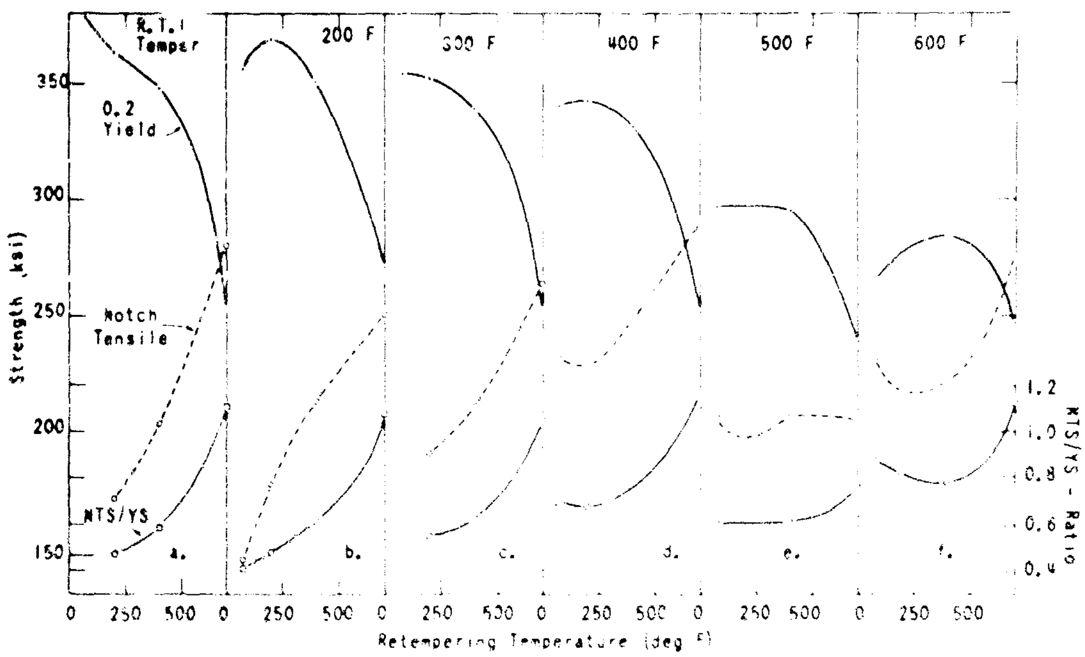

Figure 11 EFFECT OF PRESTRAINING AND RETEMPERING ON THE TENSILE PROPERTIES OF MARTENSITE

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retempering temperatures. Here it is apparent that the N.T.S/Y.S ratio increases with tempering and retempering temperatures which also result in lower yield strength.

Bainite

The effect of prestraining and retempering on the notch tensile strength of the bainite is shown in Figure 10. Although some loss in notch tensile strength is indicated for the bainite which was prestrained and retempered, particularly at room temperature and 200 F, the N.T.S./Y.S. ratio remained greater than 1. This indicates that good toughness was retained at the highest yield strength levels of 275,000 to 280,000 psi, as shown in Figure 12.

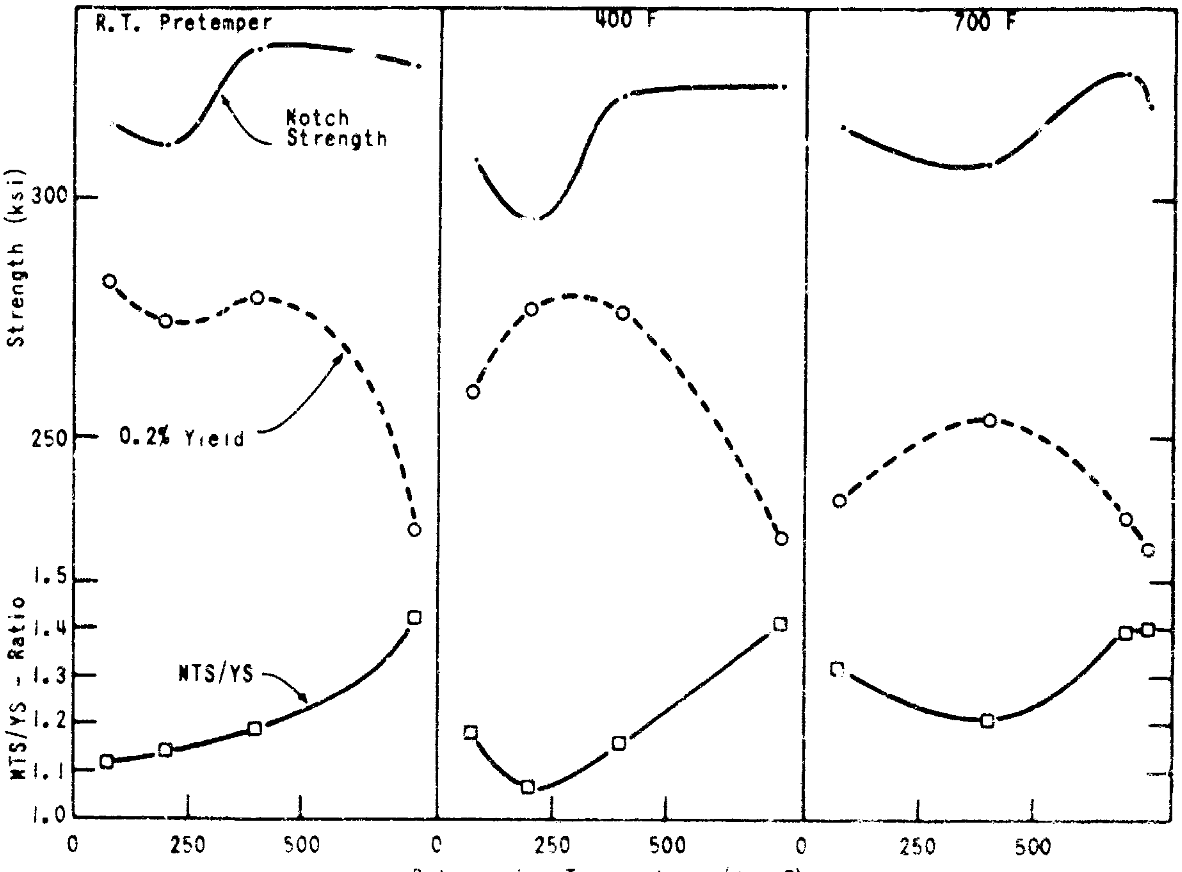

Figure 12. EFFECT OF PRESTRAINING AND RETEMPERING ON THE TENSILE PROPERTIES OF BAINITE

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Further cold working of the bainite should permit higher yield strength with good toughness.

DISCUSSION

Strength changes from the as-quenched martensite and bainite were derived in increments from three sources as follows: (1) tempering, (2) prestraining, and (3) retempering. The first, tempering, results in quite different ultimate tensile strength behaviors of the martensite and the bainite. The tensile strength of the martensite undergoes a rapid increase with decreasing tempering temperature while the effect of tempering on the tensile strength of the bainite is negligible. The yield strength for both microstructures remained comparatively constant. Also the maximum tensile strength of tempered martensite was appreciably higher than that of tempered bainite.

The effect of the second increment, prestraining, was basically the same for both microstructures. The tensile strength was increased together with the yield strength, due primarily to strain hardening; however, the rate of

increase was greater for the yield strength than for the tensile strength, resulting in a yield-tensile strength ratio approaching unity. A greater increase in both the yield and tensile strengths was apparent for the martensite and bainite initially tempered at the lower temperatures.

The third increment, retempering, generally lowered the yield and tensile strengths of the prestrained martensite and bainite when the retempering temperature was above the tempering temperature. A constant increase was noted on retempering at temperatures below the tempering temperature.

To summarize, the effect of prestraining tempered rods is to increase the strength level of both the martensite and the bainite, the effects on the martensite being greater in magnitude and more dependent upon the tempering temperatures. The role of retempering is dependent upon the tempering temperature.

Theories have been developed which attribute a portion of the strengthening on prestraining and retempering to an interaction between carbon and/or carbides and dislocations and/or vacancies, as noted in the Introduction. This type of mechanism has also been used to explain the appearance of an initial serration or sharp yield point drop in the true stress-true strain and load elongation curves.

This yield phenomenon was found in room temperature tensile tests of both the martensitic and the bainitic materials tested after prestraining. It has also been noted by others for H11 steel[14] and 4340 steel[3] processed under comparable conditions. The initial serration may be expanded into a series of serrations continuing to fracture by (1) interrupted loading (or a sufficiently slow strain rate) and (2) testing at 212 F (and probably a limited range of elevated temperatures). Specimens of the bainitic material in the tempered condition exhibit no serration or yield point in room temperature tests. This material developed serrations on testing at 212 F, suggesting a strain aging type of mechanism.

The serrations observed for both martensite and the bainite differ from those normally observed on strain aging as they were initiated at maximum load in the prestrained material and at an appreciable strain increment following maximum load in the tempered material. Also, in each material necking was initiated and continued to failure at one location.

The above suggests a dislocation-locking type of mechanism which is time-, strain-, and temperature-dependent. The increased dislocation density due to a room temperature prestrain appears to have two primary effects: (1) raise the flow stress curve and (2) cause the first serration to be initiated at a lower strain compared to the tempered material.

The notch tensile properties associated with the strengthening are noteworthy for two principal reasons. First is the insignificant loss in the notch tensile strength of the bainite on prestraining and retempering. The resulting notch tensile strength ratio greater than 1 and notch strengths

over 300,000 psi indicate the bainite is appreciably tougher than the martensite at a comparable strength level. The toughness of martensite and bainite has been reported in several investigations.[6-9,15,16] The results are contradictory, indicating that for some processing and test conditions martensite is tougher than bainite and, for other conditions, that bainite is tougher. The differences are probably due to variations in the microstructures of the bainite caused by different temperatures of the bainite formation and the presence of retained austenite.

The second observation of interest is the significant decrease in notch strength on prestraining the martensite initially tempered at 500 F, indicative of a very narrow 500 F temper embrittlement range due to prestraining.

CONCLUSIONS

1. The effects of three processing variables on the mechanical properties of martensite and bainite have been observed: (a) tempering, (b) prestraining, and (c) retempering.

The first, tempering, was most effective in decreasing the ultimate tensile strength. The yield strength was most responsive to prestraining. The retempering effect was dependent primarily upon the initial tempering temperature. The highest tensile and yield strengths were obtained with the prestrained and retempered martensite.

2. Flow curves of the tempered materials were altered by prestraining, retempering, and tension specimen test temperature and strain rate. This was shown by changes in the magnitude of the flow stress and by introduction of a yield point drop or an initial serration. The magnitude and number of serrations were also dependent upon these variables.

3. The notch strength of bainite was superior to that of martensite at comparable strength levels.

4. Evidence of temper embrittlement was observed in the prestrained and retempered martensite which was initially tempered at 500 F.

5. The effect of prestraining with a back-pull on the mechanical properties is minimal.

APPENDIX

Table I. TENSILE PROPERTIES OF MARTENSITE

Temper (deg F)	Prestrain (%)	Retemper (deg F)	Yield Strength (ksi)		Tensile Strength (ksi)	Reduction of Area (%)	Yield Strength / Tensile Strength	Notch Tensile Strength (ksi)
			0.1%	0.2%				
R.T.	0	R.T.	214.0	234.0	-	-	-	-
			200.4	220.4	346.7	17.2	0.636	177.7
			184.0		342.0	20.5	0.596	-
	3.96	R.T.	356.7	378.8	384.8	11.8	0.984	-
		200	360.2	363.4	364.4	29.6	0.998	171.5
		400	345.0	348.0	348.0	32.6	1.0	203.0
		700	252.5	253.0	256.5	37.2	0.985	280.5
R.T.	0	R.T.	241.0	250.0	320.0	30.8	0.781	170.7
			190.9	214.4	348.7	14.7	0.902	-
B.P.* = 14,500 lb	4.6	R.T.	344.0	362.5	374.0	21.8	0.97	144.3
		200	364.0	375.0	379.5	22.6	0.963	173.8
		400	360.7	362.7	362.7	24.1	1.0	192.9
		700	255.5	258.5	260.5	35.4	0.992	265.6
200	0	R.T.	212.5	234.0	236.0	-	0.992	201.3
			184.4	211.9	345.7	21.8	0.613	
	3.75	R.T.	355.5	356.0	356.0	30.8	1.0	144.1
		200	368.7	368.7	370.7	31.4	0.995	177.0
		400	348.7	350.7	350.7	30.8	1.0	212.5
		700	248.5	250.5	255.5	41.0	0.982	270.6
		R.T.	328.0	363.0	373.0	[illegible]		
200	0	R.T.	226.5	238.5	330.7	30.8	0.721	179.1
B.P. = 14,500 lb	4.4	R.T.	372.7	376.8	377.8	24.7	0.998	165.6
		200	367.7	374.7	376.8	18.4	0.995	155.8
		400	352.7	354.7	354.7	28.1	1.0	190.2
		700	251.5	253.5	256.5	36.6	0.987	257.1
		R.T.						169.3
		200						152.1
300	0	R.T.	213.4	233.0	333.7	28.1	0.699	216.4
	3.96	R.T.	342.7	353.7	358.2	30.2	0.987	
		200	339.7	351.7	358.7	26.0	0.98	190.9
		400	334.7	338.7	338.7	28.8	1.0	210.4
		700	251.0	252.0	256.5	53.6	0.982	264.2
300	0	R.T.	209.4	226.5	326.7	28.1	0.693	203.4
B.P. = 14,500 lb	4.40	R.T.	328.7	348.7	358.7	26.8	0.972	176.9
		200	351.7	356.7	362.2	26.0	0.995	169.0
		400	346.7	348.7	348.7	27.4	1.00	202.4
		700	245.5	248.5	254.5	37.8	0.976	280.6
400	0	R.T.	220.4	235.5	312.6	39.2	0.752	253.5
	3.97	R.T.	334.7	339.7	346.7	35.0	0.960	231.8
		200	334.7	341.7	344.7	33.4	0.99	227.6
		400	325.7	330.7	331.7	35.4	0.998	247.5
		700	248.5	250.5	254.5	39.4	0.985	289.9
400	0	R.T.	228.5	242.0	304.7	38.6	0.794	257.8
B.P. = 14,200 lb	4.47	R.T.	345.0	348.0	348.0	35.4	1.0	231.1
		200	344.0	348.0	350.0	29.4	0.995	241.3
		400	335.0	337.0	344.0	34.0	0.98	207.7
		700	254.0	256.0	261.0	39.8	0.981	279.4
500	0	R.T.	222.4	234.5	284.6	41.0	0.624	261.9
	4.40	R.T.	293.6	306.6	314.6	39.2	0.974	216.2
								206.7
		400	297.6	304.6	306.6	37.2	0.993	216.1
		700	246.5	249.0	250.5	39.0	0.993	214.7
		200						200.3
500	0	R.T.	224.9	238.5	282.6	37.8	0.845	199.8
B.P. = 14,300 lb	4.75	R.T	271.5	292.6	300.6	42.4	0.973	189.9
		200	274.5	292.0	303.0	36.0	0.965	176.6
		400	304.1	309.1	309.1	37.8	1.00	184.3
		700	250.0	251.5	254.5	38.6	0.987	239.3

Table I. TENSILE PROPERTIES OF MARTENSITE (continued)

Temper (deg F)	Prestrain (%)	Retemper (deg F)	Yield Strength (ksi) 0.1%	Yield Strength (ksi) 0.2%	Tensile Strength (ksi)	Reduction of Area (%)	Yield Strength / Tensile Strength	Notch Tensile Strength (ksi)
600	0	R.T.	225.5	226.0	258.5	42.4	0.874	290.2
	4.4	R.T.	252.5	265.5	277.6	42.4	0.957	232.3
		400	278.6	284.6	287.6	41.0	0.99	221.9
		600	261.5	265.0	270.0	41.0	0.961	252.6
		700	243.0	246.0	249.0	42.8	0.988	276.7
		200						217.4
600 B.P.* =	0	R.T.	224.0	226.0	260.0	42.4	0.87	257.1
14,300 lb	5.11	R.T.	259.0	269.0	272.0	38.6	0.99	255.6
		400	290.0	293.0	294.0	37.2	0.996	245.9
		600	268.0	270.0	272.0	39.2	0.993	253.1
		700	246.0	248.0	249.0	41.0	0.995	290.4
		200						242.9
800	0	R.T.	-	195.4	206.4	41.6	0.945	279.5
	10	R.T.	-	198.4	218.4	41.0	0.908	249.5
	10	400	-	217.4	228.5	37.2	0.950	-
800 B.P. =	10	R.T.	-	212.4	215.4	39.2	0.970	259.6
14,800 lb	10	400	-	227.5	234.5	35.4	0.968	227.1
1000	0	R.T.	-	176.4	187.9	42.6	0.940	271.0
	10	R.T.	-	186.4	196.4	44.0	9.948	274.0
	10	400		186.4	197.9	38.6	0.942	274.0
1000 B.P. =	10	R.T.	-	195.4	199.4	42.8	0.980	284.0
16,650 lb	10	400	-	207.4	212.9	39.8	0.973	280.0
1,150	0	R.T.	-	143.8	155.8	53.6	0.923	230.2
	10	R.T.	-	162.3	166.3	50.8	0.975	249.0
	10	400	-	170.8	177.4	45.8	0.962	262.0
1 150 B.P. =	10	R.T.	-	165.8	168.3	43.4	0.985	252.0
14,850 lb	10	400	-	174.3	177.4	47.4	0.983	270.0

*Back Pull

Table II. TENSILE PROPERTIES OF BAINITE

Temper (deg F)	Prestrain (%)	Retemper (deg F)	Yield Strength (ksi) 0.1%	Yield Strength (ksi) 0.2%	Tensile Strength (ksi)	Reduction of Area (%)	Yield Strength / Tensile Strength	Notch Tensile Strength (ksi)
R.T.	0	R.T.	188.4	198.4	240.5	56.8	0.825	332.6
	4.46	R.T.	279.6	282.6	283.1	45.2	0.999	315.5
		200	264.5	273.4	275.6	51.5	0.992	311.3
		400	269.5	278.6	280.6	50.4	0.996	331.0
		750	229.0	230.5	230.5	52.6	1.0	327.7
R.T. B.P.* = 14,200 lb	0	R.T.	191.0	200.0	245.0	54.3	0.815	337.2
	4.9	R.T.	280.0	282.0	282.0	43.2	1.0	330.3
		200	281.0	282.5	282.5	47.4	1.0	333.9
		400	279.5	280.0	280.0	48.6	1.0	317.6
		750	228.0	228.0	228.0	52.0	1.0	325.5
400	0	R.T.	186.0	195.0	242.0	54.8	0.806	326.8
	4.33	R.T.	248.0	259.0	265.0	53.6	0.978	308.2
		200	275.5	277.0	278.0	51.5	0.995	295.3
		400	272.0	277.0	278.0	49.8	0.995	321.7
		750	228.0	229.0	229.0	52.0	1.0	323.9
400 B.P. = 14,300 lb	0	R.T.	187.0	198.0	244.0	56.2	0.811	331.6
	4.9	R.T.	258.0	[illegible]	268.0	53.6	0.995	324.3
		200	280.0	282.0	282.0	50.4	1.0	326.5
		400	279.0	282.5	282.5	45.2	1.0	333.8
		750	223.0	224.5	224.5	50.4	1.0	326.8
700	0	R.T.	206.5	212.5	237.5	53.6	0.896	317.4
	4.47	R.T.	226.0	237.0	243.0	54.1	0.975	315.0
		400	250.5	254.0	255.0	52.0	0.996	307.9
		700	232.5	234.0	234.0	49.8	1.0	326.5†
		750	226.0	227.0	227.0	52.0	1.0	319.0
700 B.P. = 14,200 lb	0	R.T.	198.0	204.0	229.5	54.8	0.89	322.2
	5.04	R.T.	238.0	[illegible]	249.0	53.6	0.988	326.0
		400	261.0	264.0	264.0	48.0	1.0	302.6
		700	242.0	243.0	243.0	49.8	1.0	326.7
		750	232.0	232.0	232.0	52.0	1.0	323.0

*Back Pull

†Loaded to 15,850 lb; fixture broke. Specimen broke at 16,100 lb. on re-test.

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13 ABSTRACT

The influence of tempering, prestraining, and retempering on the strength and toughness of martensitic and bainitic 4340 steel rods was investigated. The initial heat treatment consisted of a quench and temper to obtain martensite in one group and formation of bainite at 575 F followed by tempering in the second group. Reductions of area of 4 to 5 percent were effected by cold drawing through a die with and without backpull, followed by a retempering treatment. Ultimate tensile strengths approaching 385,000 psi for the martensitic structure and 283,000 psi for the bainitic structure resulted with yield-tensile strength ratios approaching unity. Notch tensile strength of the bainite was superior to that of martensite at comparable strength levels. The prestraining also caused a yield point drop and/or serrations in the flow curves. This was influenced by specimen test temperature and strain rate, tempering temperature, and retempering temperature. (Author)

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Steel, high strength						
Mechanical properties						
Notch-tensile properties						
True stress-true strain						
Cold drawing						
Martensite						
Bainite						
Tempering						
Aging						
4340 alloy						

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